Charge Transfer Fluctuation as a Signal for QGP

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Why fluctuations?

- Sometimes physics is in the width.

- Thermodynamically interesting (heat capacity, ...).

- Bulk property : $p_T < 2\,\mathrm{GeV}$

Aren't Correlation functions better?

- Yes, of course. More fundamental and lots more info. Fluctuations are but a single aspect of them but easier to predict than the whole function.

Interesting fluctuations

- Multiplicity fluctuations (KNO? Thermal?)
- Energy fluctuation (Heat capacity?)
- ‘Charge’ fluctuation
  - Electric charge (Fractional charges?)
  - Baryon number (Fractional baryon number?)
  - Strangeness (Gluon fragmentation?)
  - Heavy quark number (Initial wave function?)
- Mean p_T/m_T fluctuation (Temperature? Heat capacity?)
- ....

Charge Transfer Fluctuations

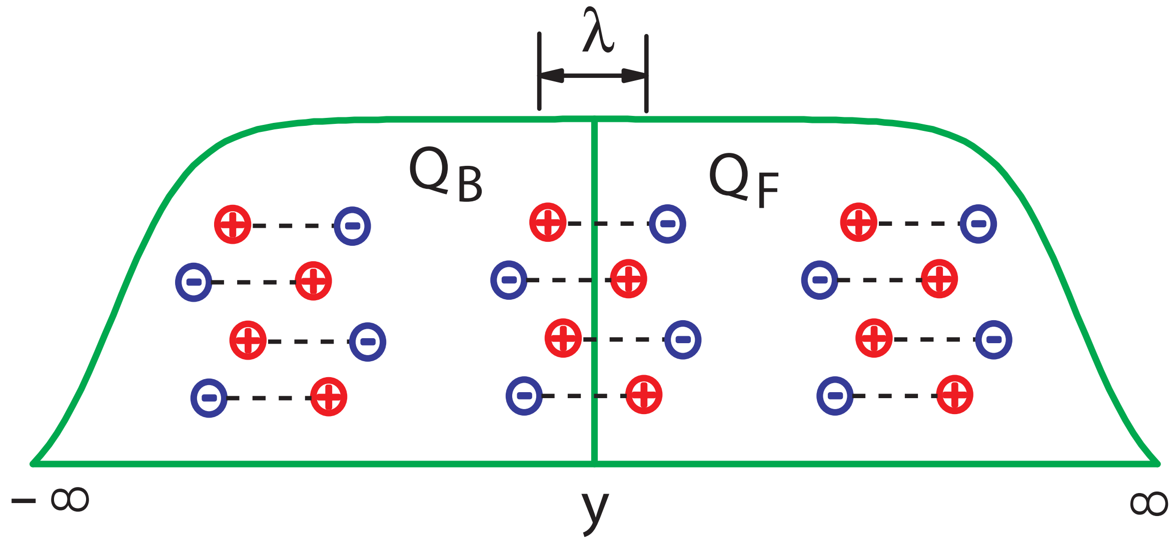
(Thomas, Quigg, Chao (1973), Shi, Jeon, hep-ph/0503085)

- Charge Transfer:

$$u(y) = \left[Q_F(y) - Q_B(y)\right]/2$$

where

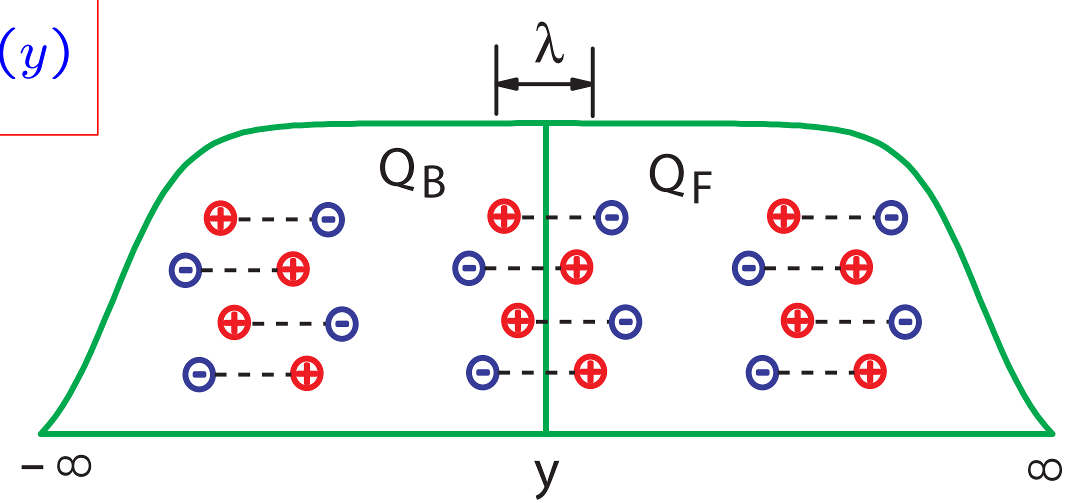
$$\begin{cases} Q_F(y) = \text{Net charge in the forward region of } y \\ Q_B(y) = \text{Net charge in the backward region of } y \end{cases}$$



- $u(y) = [Q_F(y) - Q_B(y)]/2$

- Suppose a neutral cluster R decays near y.
  - $R \longrightarrow h^+ + h^-$ with a typical $\Delta y = \lambda$
  - For each R decay, $u(y)$ changes by $\pm 1 \Longrightarrow$ Random walk
  - $D_u(y) = \langle \Delta u(y)^2 \rangle = N_{\text{steps}}(y) \approx \lambda \frac{dN_{\text{cluster}}}{dy}$
  - Since $dN_{\text{cluster}}/dy \propto dN_{\text{ch}}/dy$,

$$\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{ch}}/dy} \propto \lambda(y)$$



Charge Transfer Fluctuations

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Constant $\kappa(y)$: Thomas-Chao-Quigg Relationship

- Measure of the *local* charge correlation length

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  [Net charge fluct. and Balance func : Averaged inside the obs. window]

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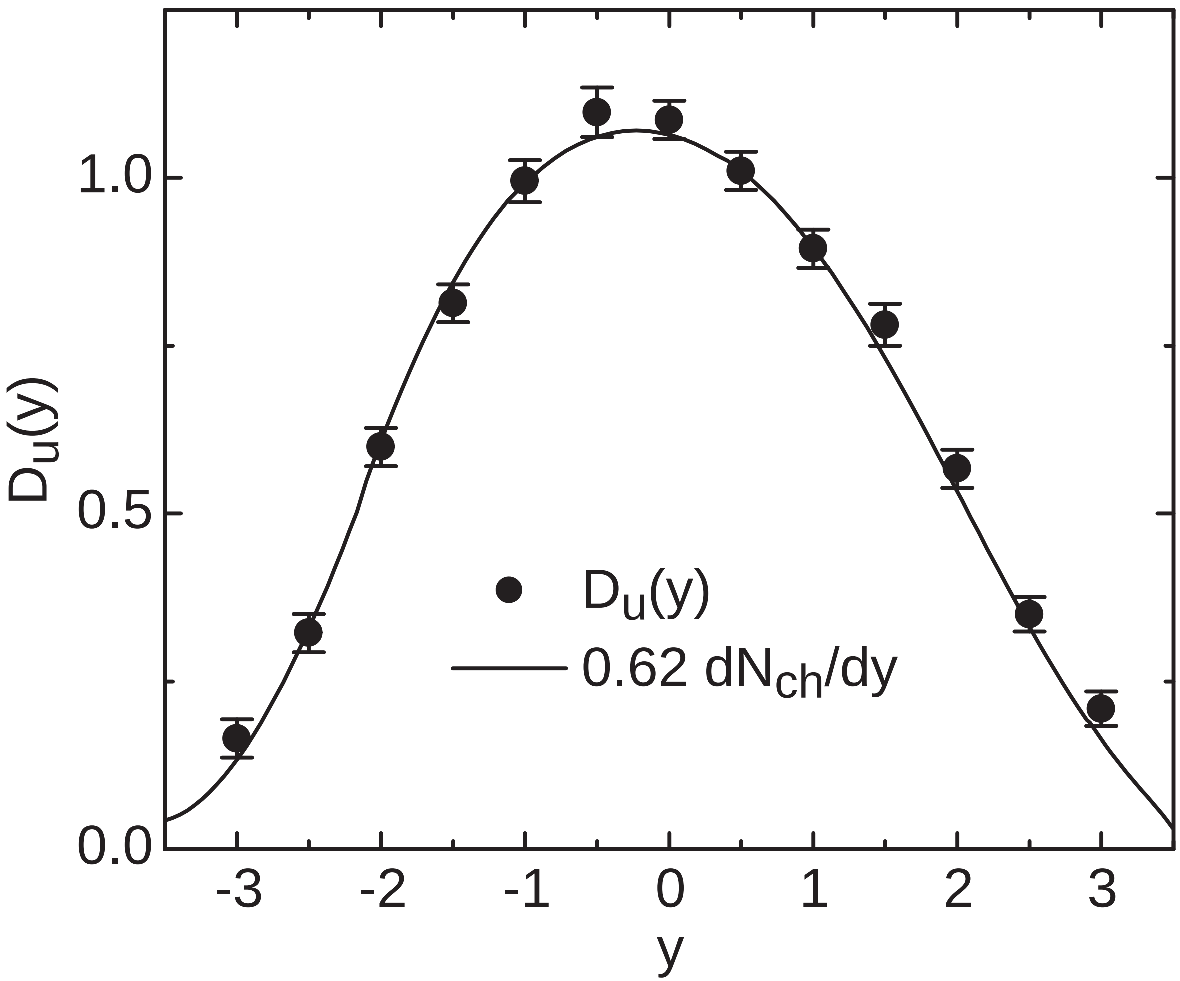
- In elementary particle collisions, $\kappa(y) \approx \text{const}$

PP @ $p_{\mathrm{max}} = 200\,\mathbf{GeV}$



Kafka et.al. PRL 34, 687, 1975

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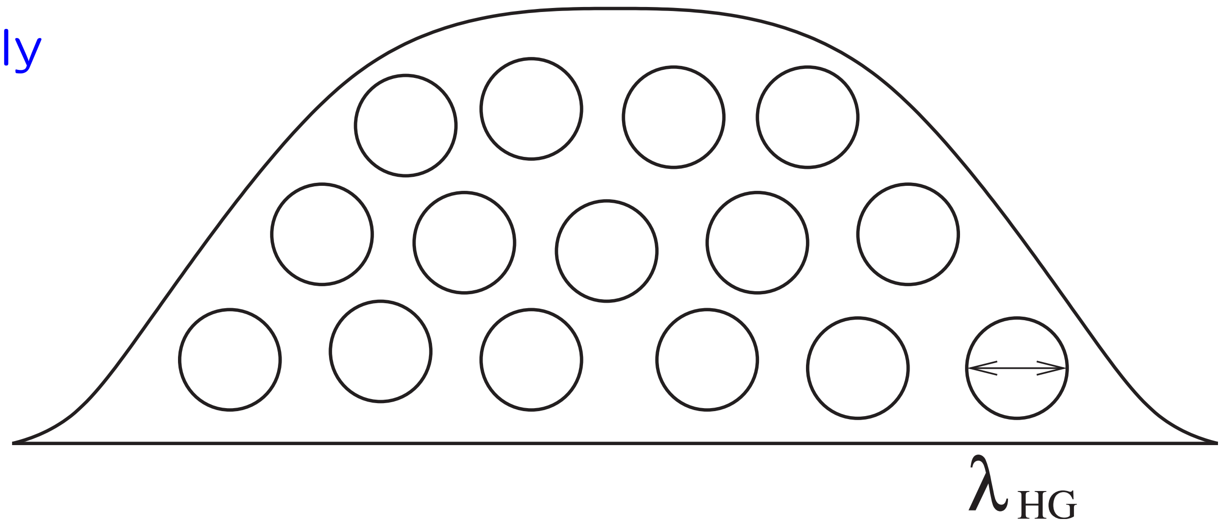
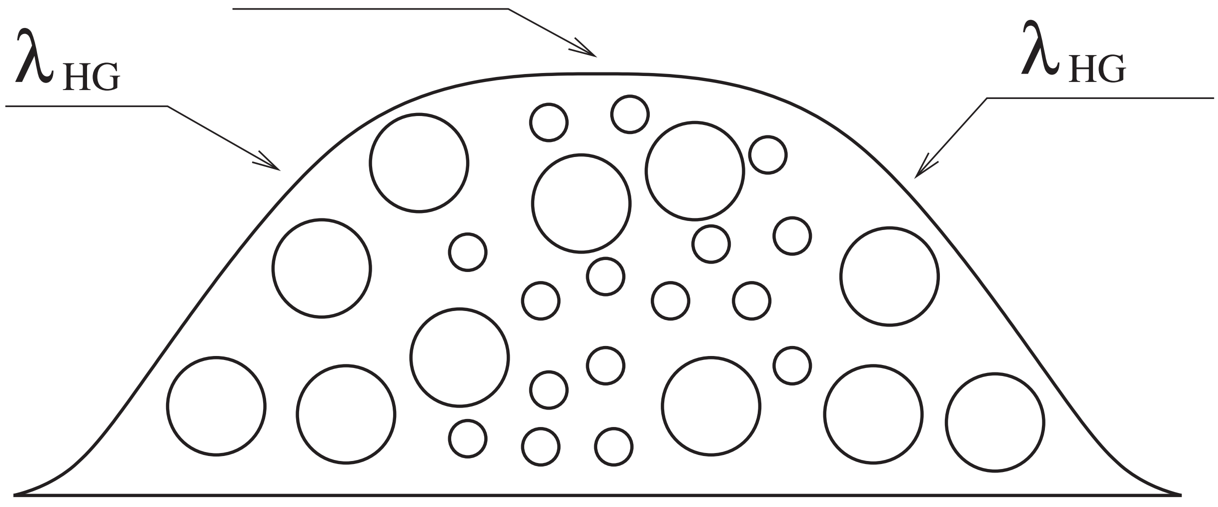
  - $\kappa_{AA} < \kappa_{PP}$
  - $\kappa_{AA}(y)$: Significantly different from constant if QGP is made only locally

In pictures

Hadron Gas only



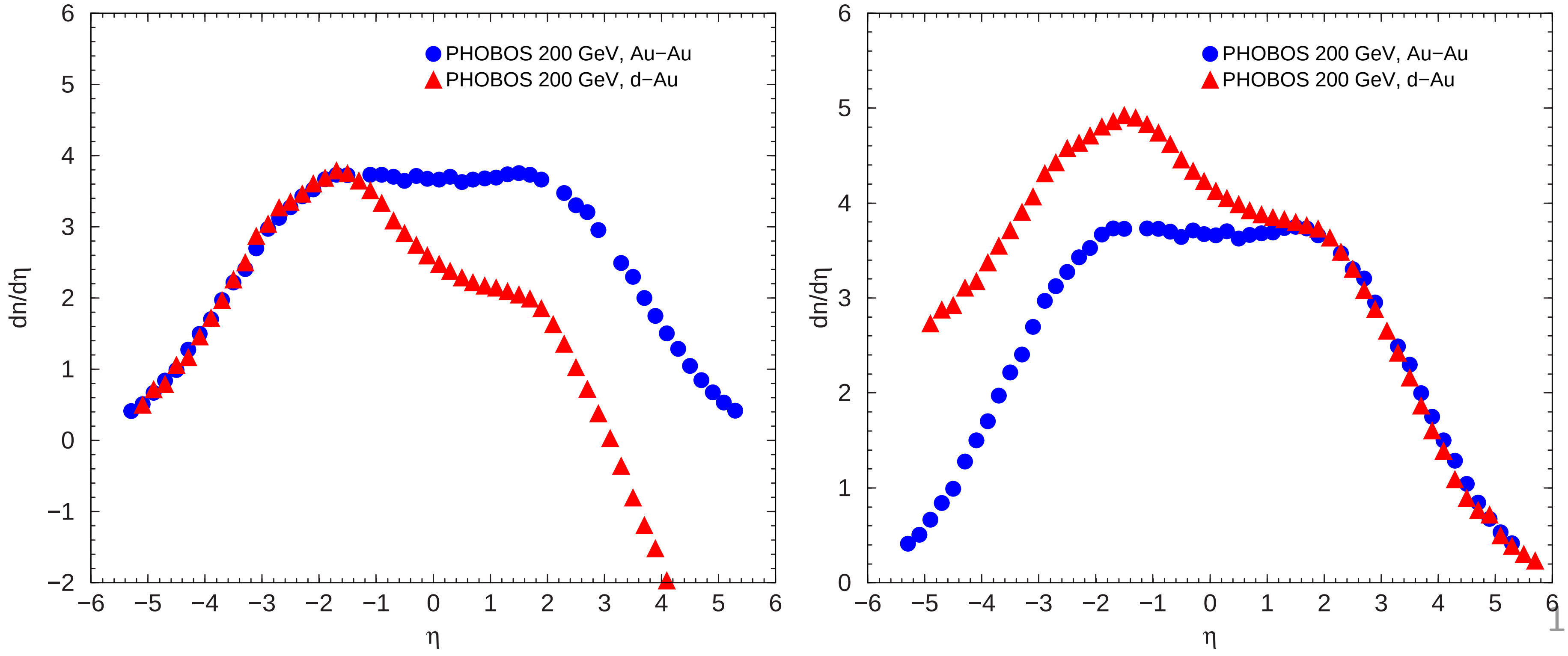
Hadron Gas + QGP $p\,\lambda_{QGP} + q\,\lambda_{HG} < \lambda_{HG}$



Extent of QGP?

- Comparing d-Au and Au-Au $dN/d\eta$ (Vertical scaling + small shifting (1 or 2 exp. bins))

- Same shapes outside the 'plateau'! (Jeon, Bleicher, Topor Pop, Phys.Rev.C69:044904,2004, nucl-th/0309077)



How small is $\lambda_{QGP}/\lambda_{HG}$?

- $\langle \Delta Q^2 \rangle_{\text{QGP}} / \langle N_{\text{ch}} \rangle \approx (1/3) \langle \Delta Q^2 \rangle_{\text{HG}} / \langle N_{\text{ch}} \rangle$
  (Fractional charges + gluons)

- If neutral clusters, this implies $\lambda_{\text{QGP}} \approx (1/3) \lambda_{\text{HG}}$

Modeling

"Correlation function has all the information."

True. Any charge fluctuation observable measures a particular aspect of

$$C_Q(y, y') = C_{++}(y, y') + C_{++}(y, y') - 2C_{+-}(y, y')$$

where

$$C_{ab}(y, y') = \frac{dN_{ab}}{dydy'} - \frac{dN_a}{dy}\frac{dN_b}{dy'}$$

- Different fluctuations emphasize different aspects of correlation.

- Fluctuations allow physical interpretation of the features through model studies.

Correlations

- Relevant to fluctuations: Single particle distributions and 2-particle correlation functions.

- Single particle distribution functions :
  $\rho_\alpha(p)dp$ = Average number of α within dp around p.

$$\int_{\Delta\eta} dp\, \rho_\alpha(p) = \langle N_\alpha \rangle_{\Delta\eta} \tag{1}$$

- 2-particle correlation functions :
  $\rho_{\alpha\beta}(p_1, p_2)\, dp_1 dp_2$ = Average number of $\alpha\beta$ pairs within $dp_1 dp_2$ around p_1, p_2

$$\int_{\Delta\eta} dp_1 dp_2\, \rho_{\alpha\beta}(p_1, p_2) = \langle N_\alpha N_\beta \rangle_{\Delta\eta} - \delta_{\alpha\beta} \langle N_\alpha \rangle_{\Delta\eta} \tag{2}$$

A toy model – "ρ" gas

- $M_\pm$ independently emitted $\pm$ particles "$\rho^\pm$" $\Longrightarrow$ $g_\pm(p_\pm)$
- M_0 neutral clusters "ρ^0" $\Longrightarrow$ $f_0(p_+, p_-)$, $g_0(p) = \int dq f_0(p, q)$
  - Single particle distributions

$$\rho_\pm(p) = \langle M+\rangle\, g_\pm(p) + \langle M_0\rangle g_0(p) \qquad (3)$$

– Two particle correlation functions

$$
\begin{aligned}
C_{++}(p_1,p_2) &\equiv \rho_{++}(p_1,p_2) - \rho_{+}(p_1)\rho_{+}(p_2) \\
&= \sum_{a=+,0}\sum_{b=+,0} \langle \delta M_a \delta M_b \rangle g_a(p_1) g_b(p_2) \\
&\quad - \langle M_+ \rangle g_+(p_1) g_+(p_2) - \langle M_0 \rangle g_0(p_1) g_0(p_2) \\
\\
C_{+-}(p_1,p_2) &= \sum_{a=+,0}\sum_{b=-,0} \langle \delta M_a \delta M_b \rangle g_a(p_1) g_b(p_2) \\
&\quad + \langle M_0 \rangle \left[f_0(p_1,p_2) - g_0(p_1) g_0(p_2) \right] \qquad (4)
\end{aligned}
$$

If Poisson-like, all terms in $C_{\alpha\beta}$ are $O(M)$.
In $\rho_{\alpha\beta}$, the leading term is $O(M^2)$ $\Longrightarrow$ f_0 is hidden.

QGP vs. Hadron gas

- Color fluctuation: Hadrons are all color neutral $\Longrightarrow$ Difficult to observe color fluctuation
- Charge fluctuation: Quarks have fractional charges $\Longrightarrow$ Less charge fluctuation per charged degree of freedom
- There are gluons: Gluons contribute to the entropy but not to the charge fluctuation $\Longrightarrow$ Less charge fluctuation per charged degree of freedom

Final hadron spectrum : Neutral rich

A Simple Neutral Cluster Model

[Similar to the old ρ, ω model and Bialas et.al.'s Acta Phys. Polon. B6, 39, 1975 model]

- Make up an event with $M_0 + M_+$ positive particles and $M_0 + M_-$ negative particles by sampling

  $$\rho(y_+, y_-) = R(y_+, y_-|Y)F(Y)$$

  M_0 times for $(+-)$ pairs and by sampling

  $$g(y) \approx F(y)$$

  $M_\pm$ times for un-paired charged particles.

$F(Y)$: Cluster rapidity distribution, $Y = (y_+ + y_-)/2$.

$R(y_+, y_-|Y)$: Rapidity distribution of the daughters given Y.

Models

- Different choices of R and F $\Longrightarrow$ Different Models

- For instance, Bialas et.al.'s model is equivalent to sampling

$$\rho_{75}(y_+, y_-) = f(y_+|Y)f(y_-|Y)F(Y)$$

  Correlation provided by integration over Y.

- Our model: Two different scenarios

  – Single species of neutral clusters ($\sim$ Hadronic): Sample

$$\rho(y_+, y_-) = R(y_+ - y_-|Y)F(Y)$$

  where ($M_\pm = 0$)

$$F(Y) = \text{Wood-Saxon}$$
$$R(y|Y) = C \exp\left(-|y|/\lambda\right)$$
$$\text{Or}$$
$$R(y|Y) = C' \exp\left(-y^2/2\sigma^2\right)$$

  Explicit charge correlation with const. λ or σ

Models – Cont.

- Single component model: $D_u(y) = \kappa dN/dy$ means

$$\int_{-\infty}^{y} dy' \int_{y}^{\infty} dy''\, f_0(y', y'') = \kappa \int_{-\infty}^{\infty} dy'\, f_0(y, y')$$

Solutions in two extreme cases:

  – Indenpendent (no cluster) : $f_0(y, y') = g(y)g(y'')$

$$g(y) = \frac{1}{4\kappa} \frac{1}{\cosh^2(y/2\kappa)} \propto \frac{dN}{dy}$$

$\Longrightarrow$ Does not correspond to real spectra.

  – 2 particle cluster: $f_0(y, y') = R(y_{rel})F(Y)$ with $y_{rel} = y - y'$ and $Y = (y + y')/2$

$$f_0(y, y') = \frac{1}{4\kappa} \exp\left(-\frac{|y_{rel}|}{2\kappa}\right) F(Y)$$

Models – Cont.

- Our model:

  Second scenario:

  Two species of neutral clusters ($\sim$ Hadronic + QGP):

  Sample

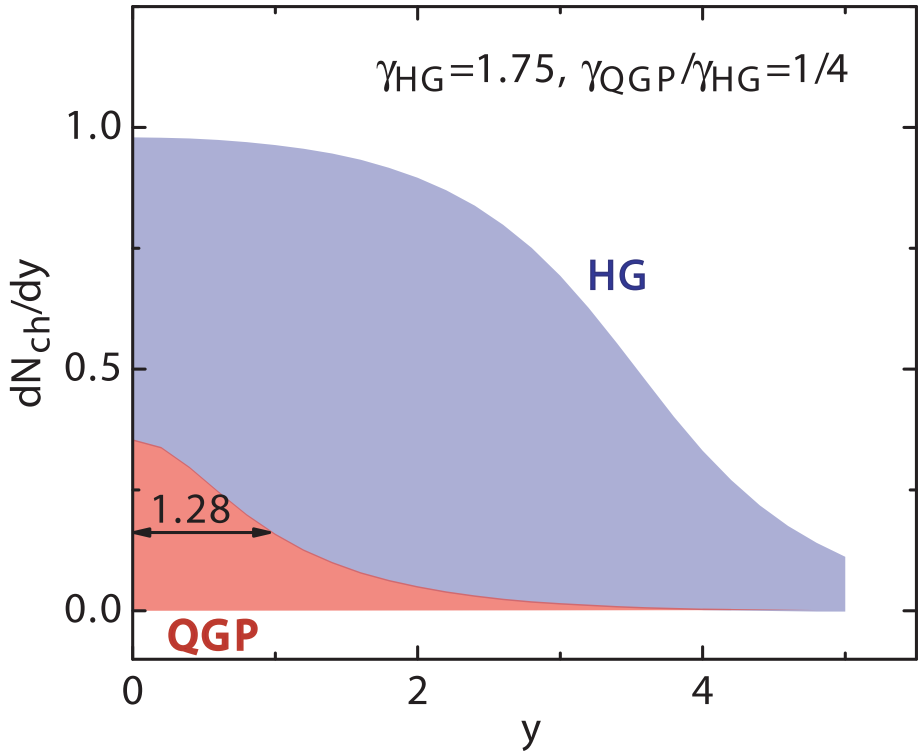
  $$\rho_H(y_+, y_-) = R_H(y_+ - y_-|Y)F_H(Y)$$

  and

  $$\rho_{QGP}(y_+, y_-) = R_{QGP}(y_+ - y_-|Y)F_{QGP}(Y)$$

  with $\lambda_{QGP} \approx (1/4)\lambda_H$

  so that

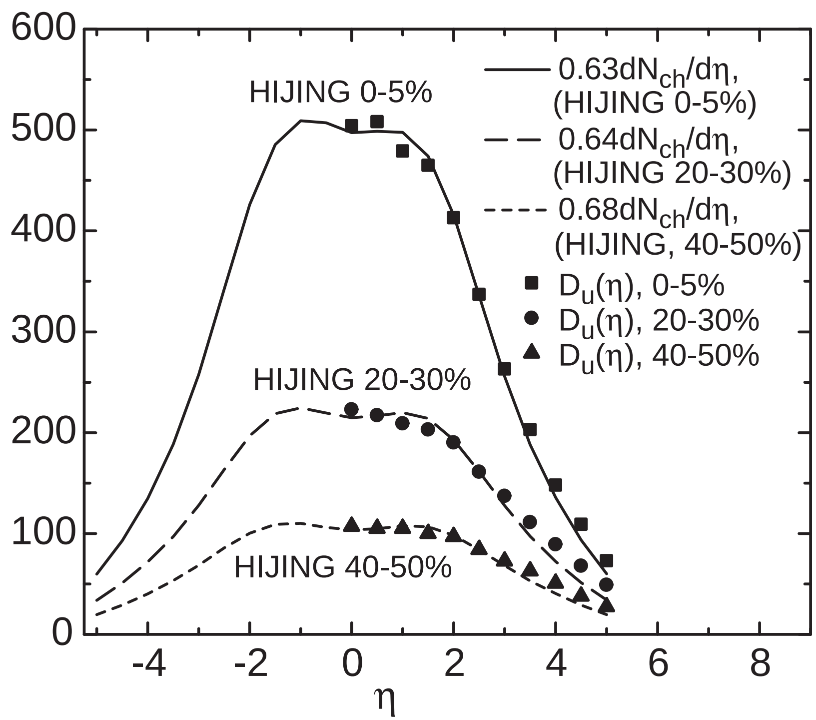


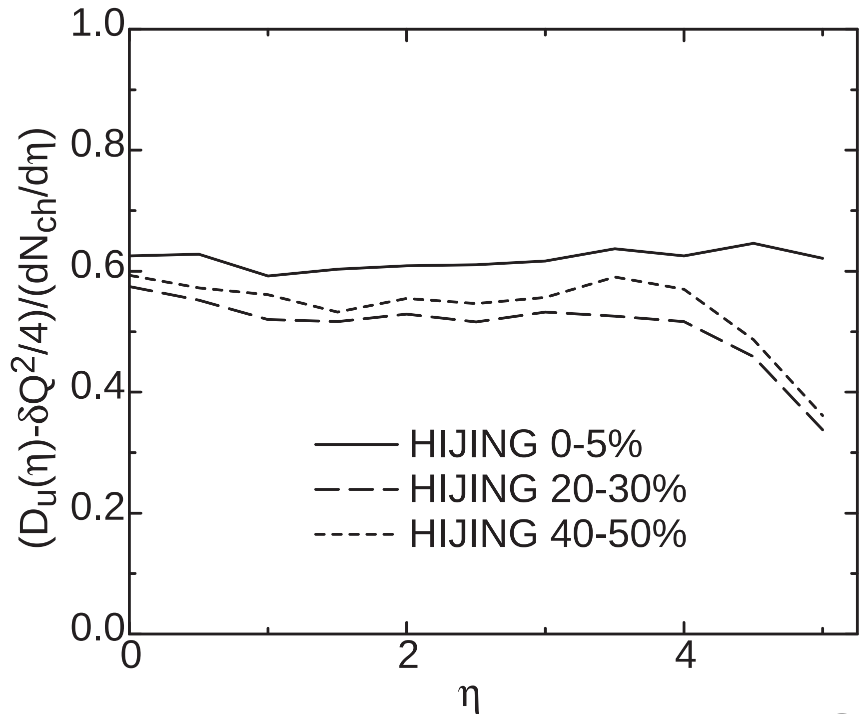
Single Component Model

- $\rho(y_+, y_-) = \exp(-|y|/\lambda)\, F(Y)$ is an exact solution of the Thomas-Chao-Quigg relationship

- $\rho(y_+, y_-) = \exp(-y^2/2\sigma^2)\, F(Y)$ is an approx. soln.

- Hadronic models $\Longrightarrow$ constant κ





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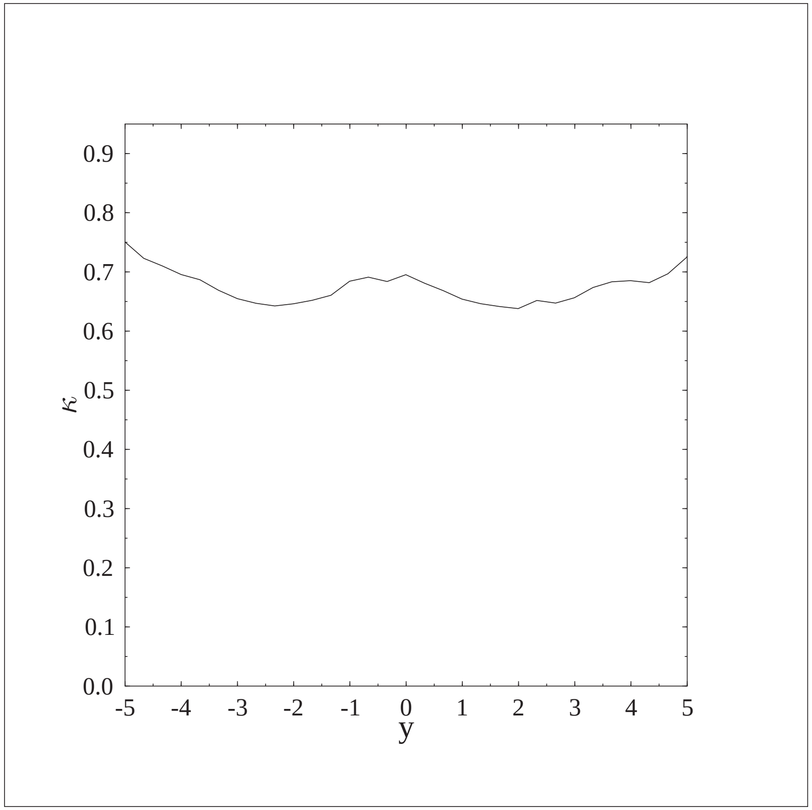
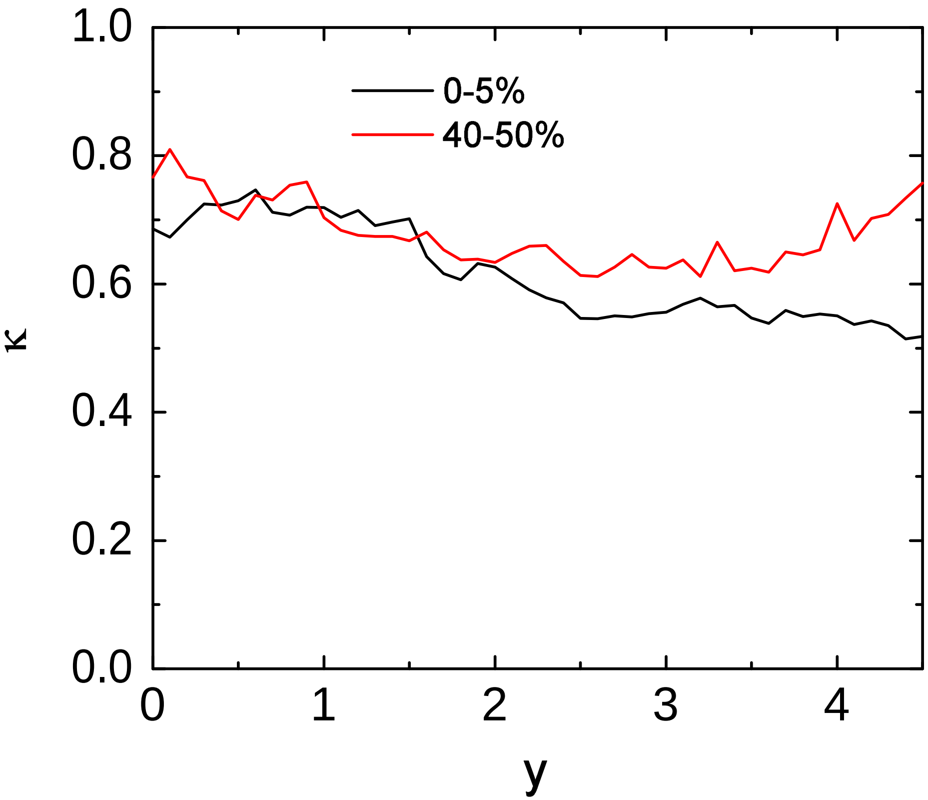
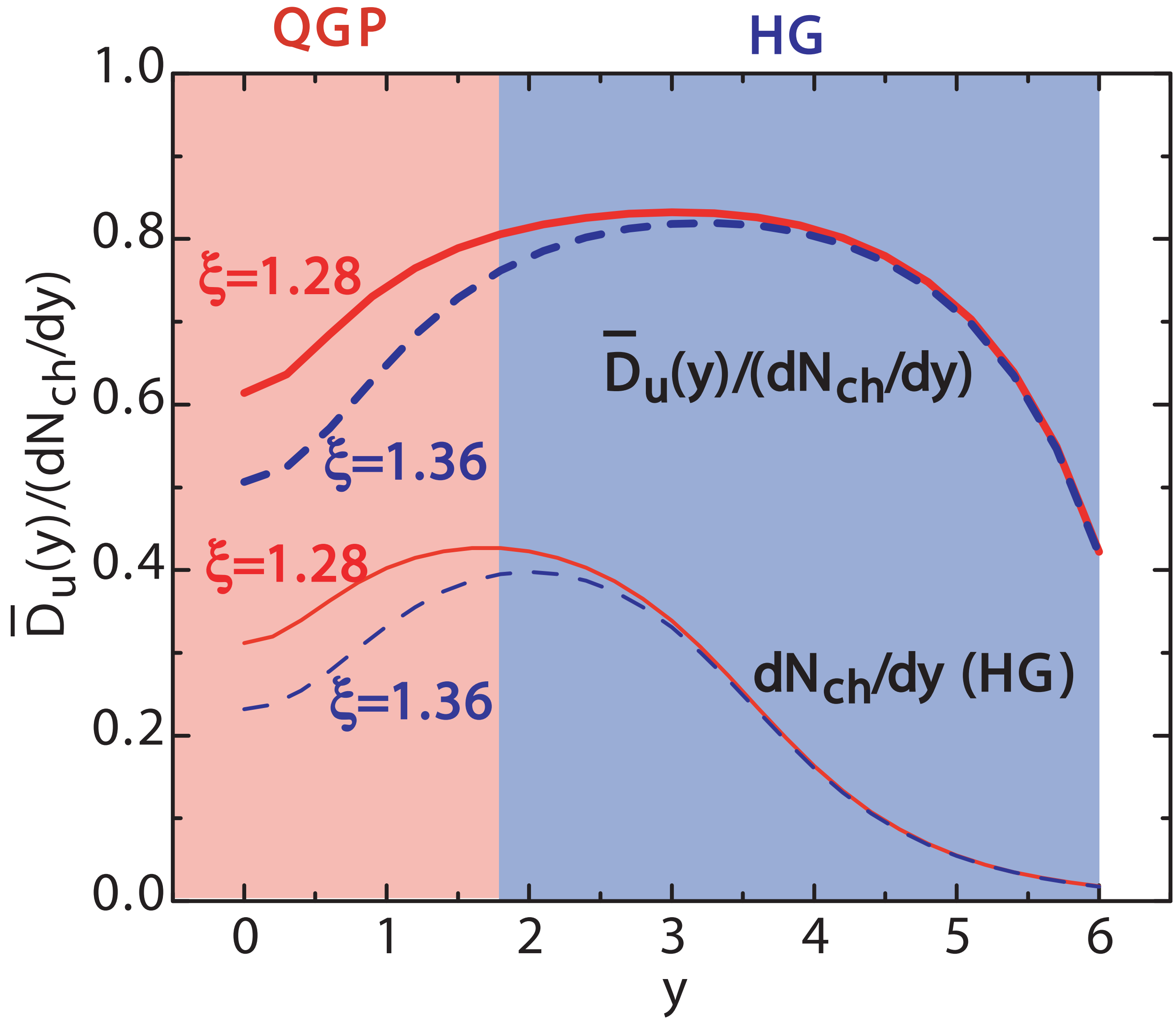




UrQMD, Central 6 %

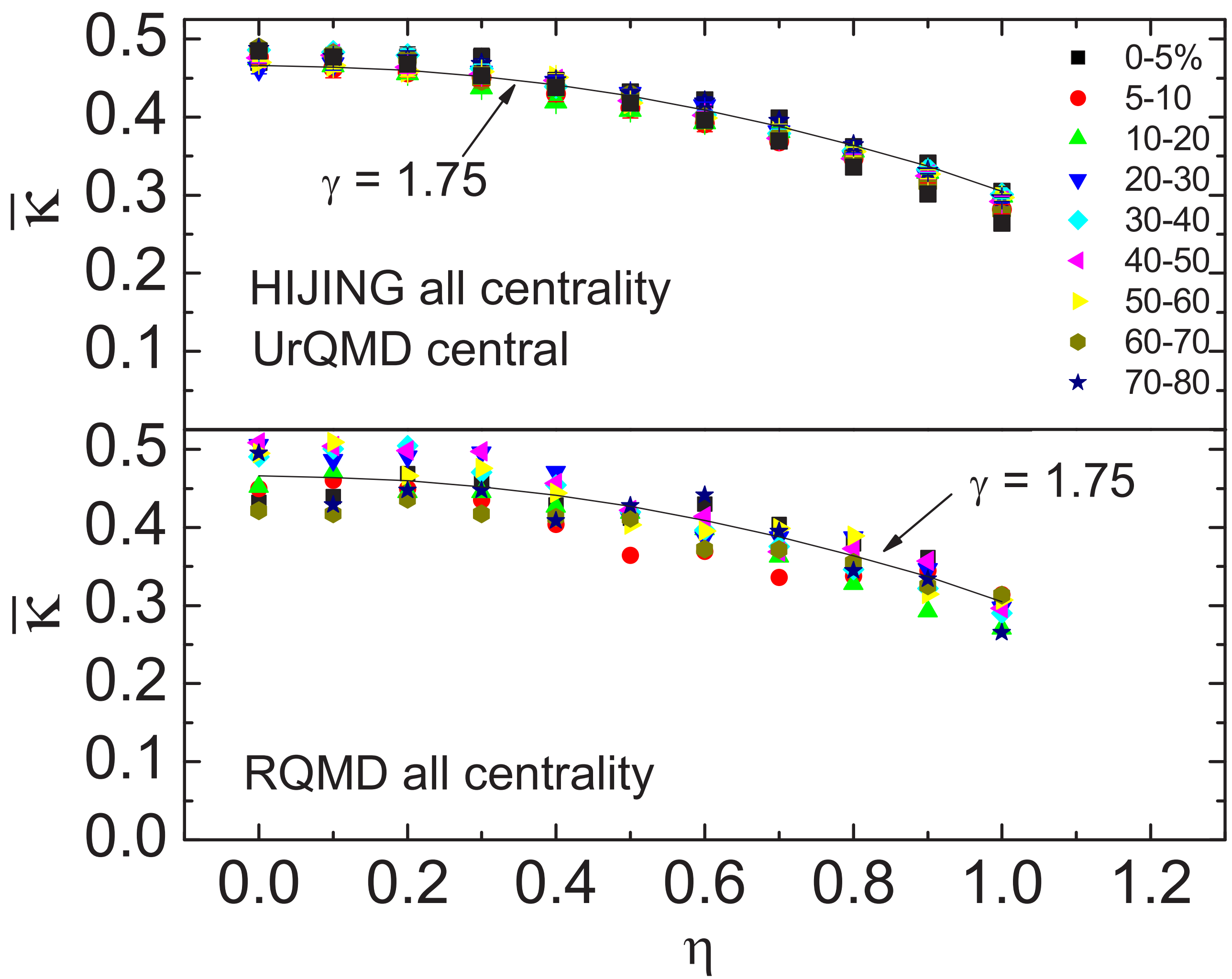
RQMD, Central, Semi-Peripheral

HG + QGP − Full η space



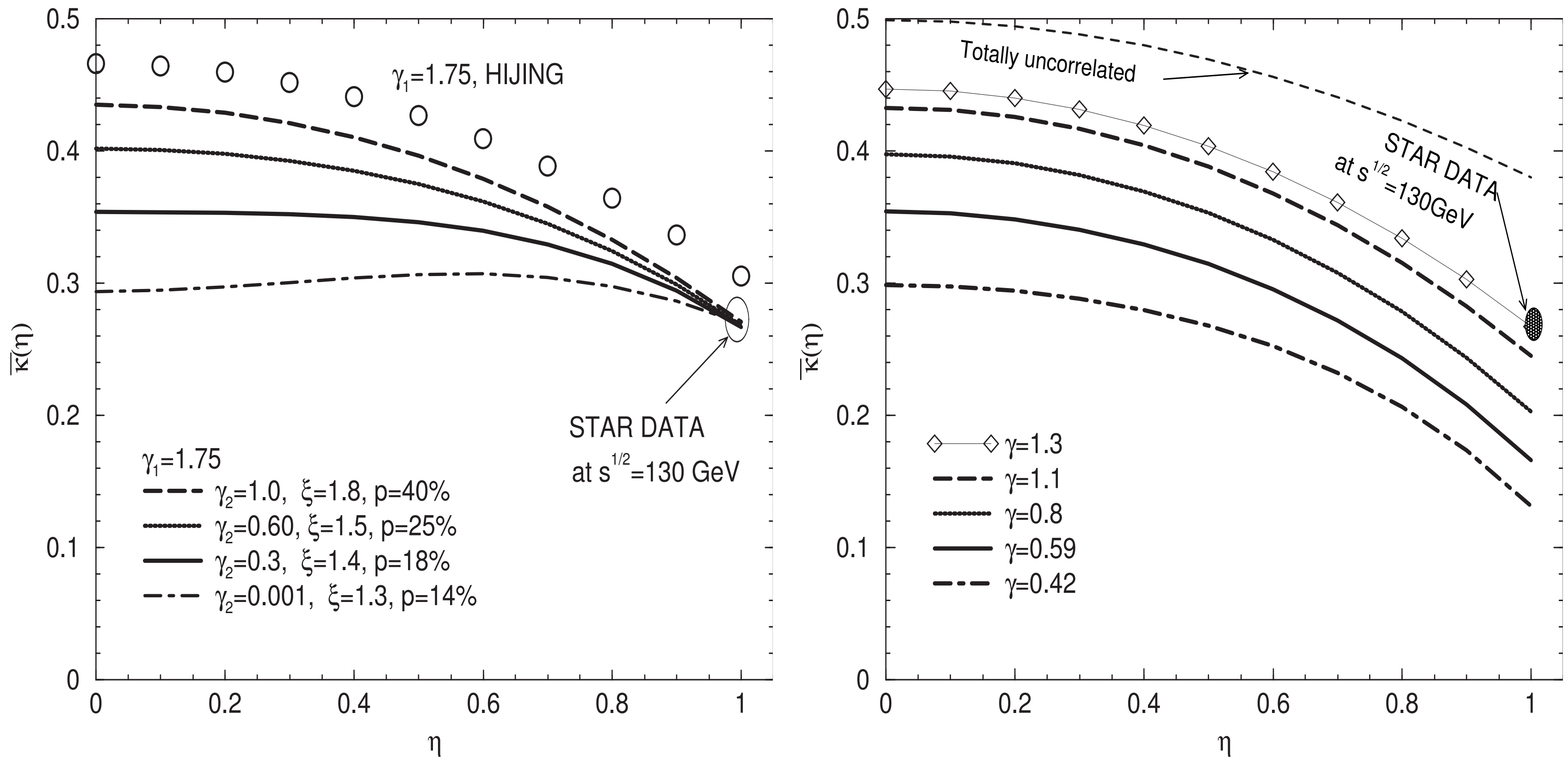
HG – STAR acceptance

Hadronic models with the single component results



HG + QGP – STAR acceptance

End point fixed by $\langle \Delta Q^2 \rangle / N_{ch}$



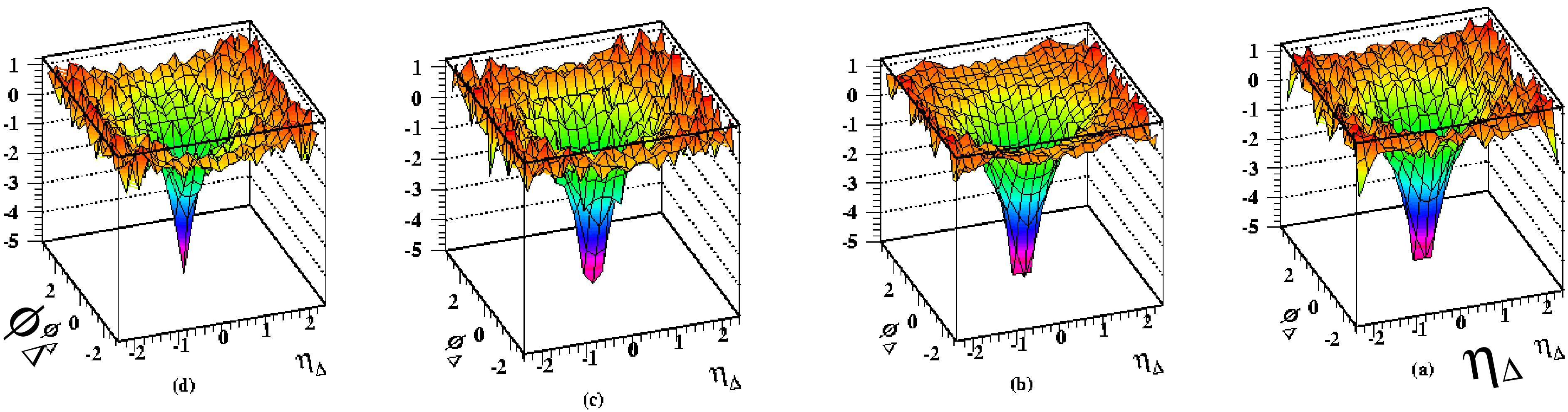
Charge difference η, ϕ correlations:

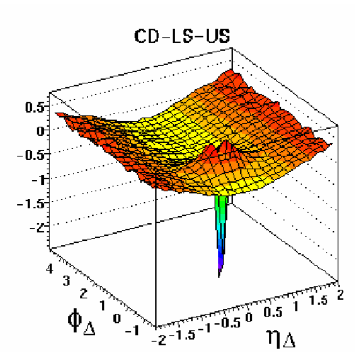
Au- Au 130 GeV Like- Unlike Charge Difference

Lanny Ray, Corr.& Fluct. in RNC 2005

Is the medium partonic or hadronic?

peripheral ⟷ central





p- p

STAR preliminary

J. Adams et al. (STAR), nucl- ex/ 0406035.

~300k events
$0.15 < p_t < 2$ GeV/ c
$|\eta| < 1.3$, full $\phi = 2\pi$
merging & HBT cuts applied

Development of 2D symmetric correlation shape and increased amplitude.

η, φ charge difference correlations for 62 GeV Au-Au

STAR preliminary

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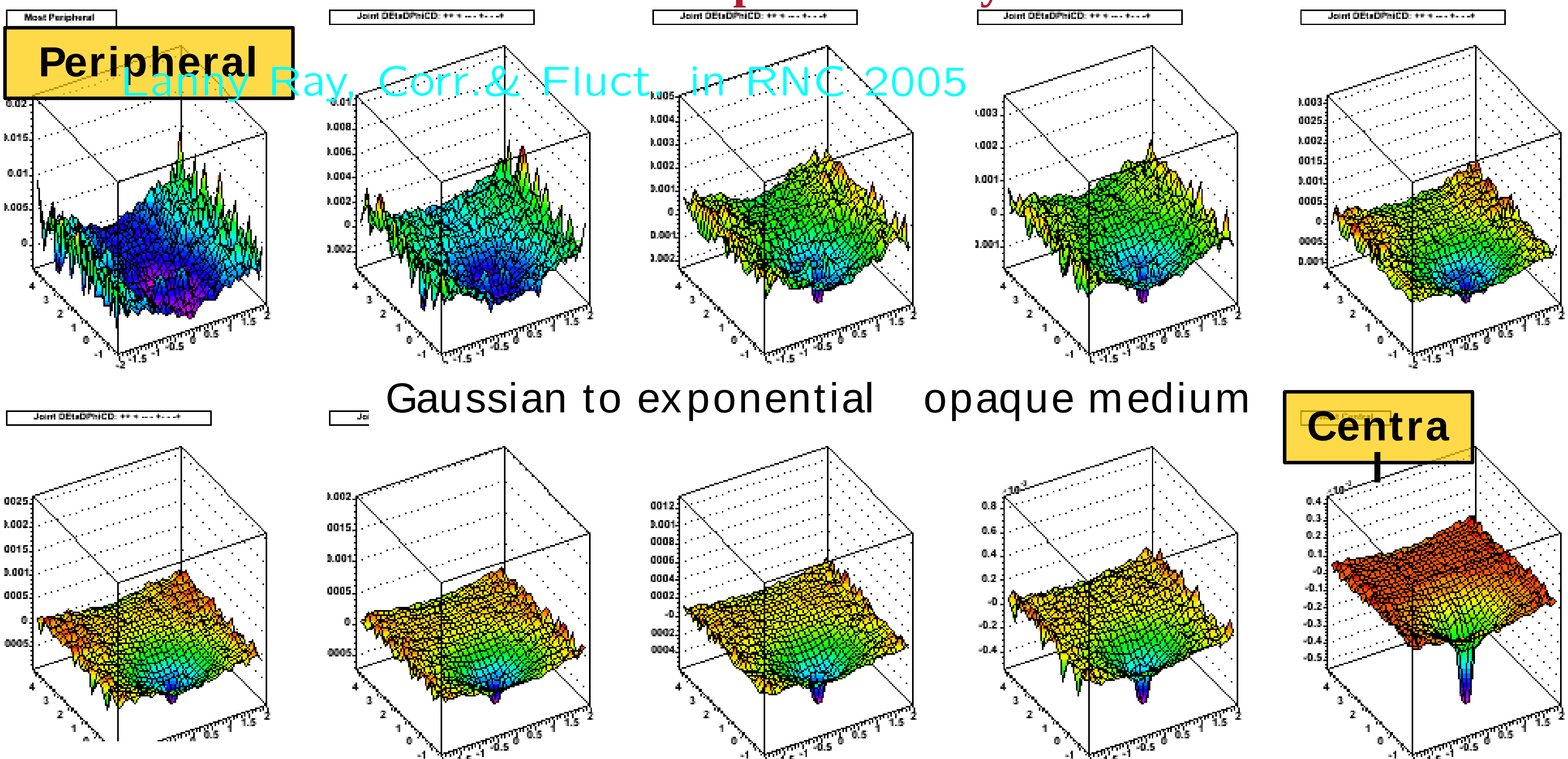
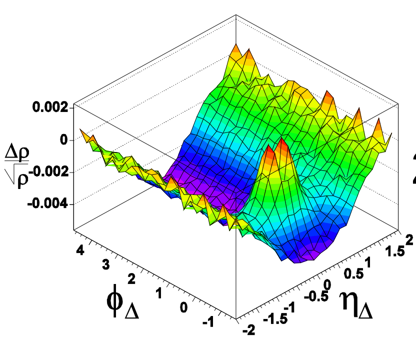
Peripheral



Gaussian to exponential   opaque medium

Central



p-p
200 GeV

Evolution from 1D string fragmentation to at least 2D hadronization

$0.15 < p_t < 2$ GeV/c
$|\eta| < 1.0$, full $\phi = 2\pi$
merging & HBT cuts applied

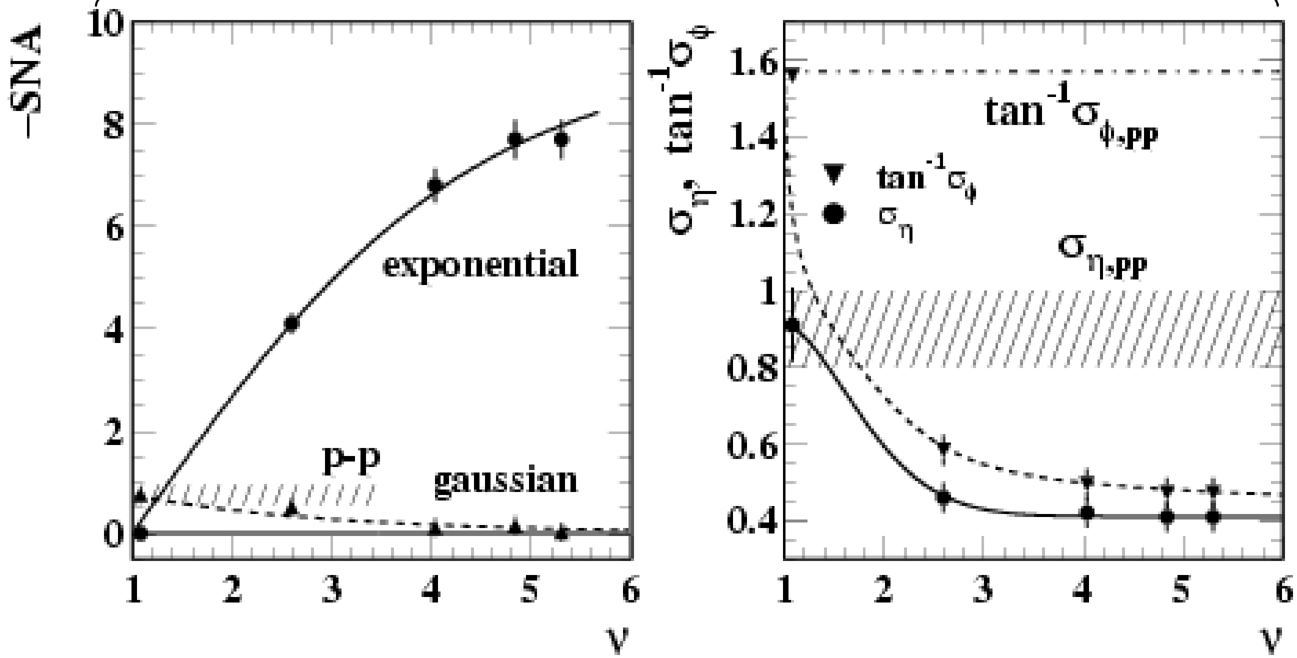
Au- Au 130 GeV Like- Unlike Charge Difference – model fit

Model Fit:

Lanny Ray, Corr.& Fluct. in RNC 2005

$$F = A_0 + A_1 e^{-\left[\left(\frac{\phi_\Delta}{\sqrt{2}\sigma_{\phi_\Delta 1}}\right)^2 + \left(\frac{\eta_\Delta}{\sqrt{2}\sigma_{\eta_\Delta 1}}\right)^2\right]^{1/2}} + A_2 e^{-\left(\frac{\eta_\Delta}{1.5\sqrt{2}}\right)^2}$$

offset dominant exponential peak weak gaussian



1D string fragmentation correlation structure quickly dissolves as we saw for the away- side CI structure.

…and approaches a 2D hadronization geometry, *i.e.* symmetric widths on ϕ_Δ, η_Δ, with exponential attenuation suggesting an opaque medium.

Conclusions

- Charge transfer: $u(y) = (Q_F(y) - Q_B(y))/2$
- $\kappa(y) \equiv \langle \Delta u(y)^2 \rangle / dN_{\rm ch}/dy$: A measure of *local* charge correlation length $\Longrightarrow$ Captures *inhomogeneity*
- QGP may be created in a small region around midrapidity. As collisions become more central
  - Large acceptance: $\kappa(y)$ develops a dip in the middle
  - Small acceptance: $\kappa(0)$ becomes smaller faster than $\kappa(y_o)$ $\Longrightarrow$ Flattening
- Net baryon transfer fluctuation. Net strange transfer fluctuation
- $\langle \Delta N_{\rm ch}^F(y) \Delta N_{\rm ch}^B(y) \rangle$